On-site Sensor Noise Evaluation and Detectability in Low Cost Accelerometers

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Abstract: Seismic networks help understanding the phenomena related with seismic events. These networks are employing low-cost accelerometers in order to achieve high-density deployments enabling accurate characterisation (high resolution) of strong earthquake motion and early warning capabilities. In order to assess the applicability of low-cost accelerometers in seismology, it is essential to evaluate their noise characteristics and identify their detectability thresholds. In this paper, a method is proposed that provides an indication of sensor noise, being demonstrated on different sensors. The method is designed to adapt to a sensor's characteristics while on-site and in-operation, thus removing potentially related logistical and maintenance bottlenecks.

1 INTRODUCTION

Seismic events can be extreme and severe threats to humanity, causing a heavy death toll, serious destruction and damage. Helping to understand these phenomena, seismic networks have been deployed in increasing number, filling in gaps in the global coverage and improving our understanding of the physical processes that cause earthquakes.

For example, Portugal has made a significant effort to develop the Broadband Portuguese seismic network integrating seismological stations supporting real-time monitoring of the earthquake activity (Caldeira *et al.*, 2007). The Portuguese national network (Instituto Português do Mar e da Atmosfera - IPMA) is the seismic monitoring of all the Portuguese territory, from the Azores and Madeira archipelagos to the mainland territory, covering the extensive Azores-Gibraltar plate boundary segment. This national network also contributes to global monitoring efforts.

EMSO-PT (http://emso-pt.pt/), the Portuguese counterpart of the European Multidisciplinary Seafloor and water column Observatory (EMSO), is an infrastructure jointly funded by the Portuguese government and the European Commission that aims to create and develop infrastructures for scientific and technological research within the scope of Marine Sciences. One the goals of EMSO-PT is to improve the national seismic monitoring network, thus allowing for the development of an Earthquake Early Warning System (EEWS), including those generated in the Atlantic region in and adjacent to the Portuguese territory. Considering the seismogenic Eurasia-Nubia plate boundary located south of mainland Portugal, current efforts by the *Instituto de Ciências da Terra* (ICT), University of Évora (UE) and IPMA aim to densify the seismic network in the extreme west of the Algarve.

A paradigm change occurred in the United States by deploying high density seismic networks with the capability to record the propagation of seismic activity in high resolution: The California Institute of Technology (CalTech) that established the Community Seismic Network (CSN), an earthquake monitoring system based on a dense array of low-cost acceleration sensors (more than 1000) aiming to produce block-by-block strong shaking measurements during an earthquake (see http://csn.caltech.edu/, last accessed 2020/08/14); The University of Southern California's (USC) Quake-Catcher Network (QCN) began rolling out

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6000 tiny sensors in the San Francisco Bay Area, being part of the densest networks of seismic sensors ever devoted to study earthquakes in real time (see https://quakecatcher.net/, last accessed 2020/08/14).

Following this trend, the ICT and UE are developing the Seismic Sensor Network Alentejo (SSN-Alentejo) that brings the most dense seismic sensor network ever deployed in Portugal. This novel network plans to deploy 60 low-cost sensors distributed in a mesh configuration spaced on average 10 km and covering an area of about 5000 square kilometres (Manso *et. al*, 2020).

A high dense network-enabled seismic network operating in the principle of "live" data brings the opportunity to explore new applications in seismology, including real-time earthquake detection, more accurate characterisation (high resolution) of strong earthquake motion and the generation of *Shakesmaps* in near real-time.

The remainder of this paper is organised as follows. Section 2 presents the background for this work, describing the relevant characteristics of low-cost accelerometers. Section 3 presents an analysis of sensor noise based on measurements collected from accelerometers, describing a suitable method for on-site and while in-operation. The method is used to determine the sensor detectability threshold related with seismic activity. Section 4 concludes this paper.

2 BACKGROUND

In the last years, sensors and sensing network technology evolved at a fast pace, resulting in improved performance (resolution, sensibility and processing capacity), operation (energy efficiency, operation time) and connectivity (broadband communications), at significant cost reduction. Low-cost Micro-Electro Mechanical Systems (MEMS) accelerometers, in particular, demonstrated the capability to generate relevant data for seismic analysis in dense deployment contexts (Lainé and Mougenot, 2014).

MEMS technology has enabled the mass production of small size accelerometers. Capacitive accelerometers, in particular, are highly popular due to reduced cost, their simple structure, and the ability to integrate the sensor close to the readout electronics. When subjected to an acceleration, the inertial mass shifts cause a proportional change in capacitance. By measuring the capacitance change, the acceleration can be calculated.

In order to properly exploit its data, it is important to take into account MEMS benefits and limitations, (Farine *et al.*, 2003; Evans *et al.*, 2014; Manso *et al.*, 2017) including: adequate sensitivity, noise level, and range (measured in g) to be applicable to earthquake strong-motion acquisition (M>3), however, limited by the *high* level of instrumental self-noise especially affecting measurement of low frequency weak-motion forces; well fit to measure high frequency (>40Hz) ground motion since their resonant frequency (typically above 1 kHz) is far above the seismic band pass; measure the gravity acceleration component thus providing a useful reference for sensitivity calibration and tilt measurement; have high acceleration ranges (several g) and can sustain high acceleration (several hundred g); complement broadband seismometers by detecting weak high frequency signals.

There is a wide range of low-cost accelerometers built for different purposes and exhibiting different characteristics. Concerning seismological applications, the following parameters should be taken into account: **Range:** Specifies the minimum and maximum acceleration values it can measure. It is often represented relative to g (e.g., ±2g); **Resolution:** Specifies both (i) the degree to which a change can be detected and (ii) the maximum possible value that can be measured. For example, a digital sensor with 16-bits resolution is able to quantify 65536 possible values. If the scale is set to ±2g (hence, a 4g range) the minimum possible change that can be detected is about 61µg; **Noise density:** Accelerometers are subject to noise produced by electronic and mechanical sources. Since they have a small inertial mass, noise increases at low frequencies. The noise density is often represented in terms of power spectral density (PSD) and is expressed as g/√Hz. It varies with the measurement bandwidth: when multiplied by it, the resulting value represents the minimum acceleration values that can be resolved; **Bandwidth:** Specifies the frequency range that the sensor operates in. It is limited to the natural resonance frequency of the mechanical structure of the accelerometer itself, which is typically very high (>kHz); **Sample rate:** Specifies the number of measurements (samples) per second.

This paper main focus is to observe the presence of sensor noise among several accelerometers. The most relevant parameter is therefore "Noise density". Next, an analysis of sensor noise measured from different accelerometers is provided.

3 NOISE ANALYSIS OF LOW-COST ACCELEROMETERS

The main limiting characteristic of consumer-based MEMS accelerometers in seismological applications is the presence of sensor noise that is originated from the sensor's electrical and mechanical components. Ultimately, the sensor noise determines the minimum resolution of the sensor. Typically, accelerometers' manufacturers provide in the respective datasheets an indication of sensor noise via the parameter "power spectral density" (PSD) that is measured in g/√Hz. Multiplying the PSD value by the square root of the measurement bandwidth gives the root mean square (RMS) acceleration noise, which is the minimal resolvable value for acceleration (NXP, 2007). It is noted that noise increases with bandwidth.

In this chapter, an indication of sensor noise is measured by deploying and collecting acceleration data from several accelerometers while at rest position. The sensor noise assessment is made by calculating the standard deviation (eq. 1) of the signal (calculated using a "moving window" of 100 samples), after removing the DC value. The lower the standard deviation the lower the sensor noise.

$$\sigma = \sqrt{\sum \frac{(x_i - \mu)^2}{N}} \quad (1)$$

Where: i is the sample number, x_i is the measurement related with sample i, μ is the mean value and N is the sample size.

The environment where accelerometers are installed might be affected by external factors (e.g., traffic or seismic activity), which can be registered by accelerometers and should be excluded from the sensor noise analysis. In order to exclude these "signals" from "noise", a threshold logic is defined and implemented as follows:

let $\sigma(n)$ be the standard deviation related with sample window n
let σ_{min} be the registered minimum standard deviation for the running period

if ($\sigma(n) > \sigma_{min} . Threshold$) then
 is signal
else
 is noise
endif

The first part of the analysis uses dedicated accelerometers operating at different bandwidth, while the second part compares the sensor noise in dedicated accelerometers and consumer smartphones. Note that this analysis assumes a "quiet" environment, thus the presence of background environmental noise is not taken into account.

3.1 Sensor Noise in Dedicated Accelerometers

In this subchapter, an indication of sensor noise is measured in two dedicated accelerometers, namely:

- **Analog ADXL355**, a 3-axis digital sensor with 20-bit resolution, noise density (as PSD) of 25µg/√Hz. (source: https://analog.com)
- **Invensense MPU-6050** with 16-bit resolution, noise density (as PSD) of 400µg/√Hz. (source: https://www.invensense.com)

Based on the specifications, the ADXL355 sensor noise is substantially lower (16x less) than the MPU-6050. Moreover, sensors are setup to work at different bandwidth in order to observe its effect in sensor noise.

The results are presented next.

3.1.1 ADXL355 Measurements

The ADXL355 is setup to operate in three different sampling frequencies: 15Hz, 100Hz and 1KHz. The measured magnitude acceleration values subtracted by the average (in g) are presented in Figure 1. As it can be seen, the magnitude of the acceleration increases with the sampling frequency.

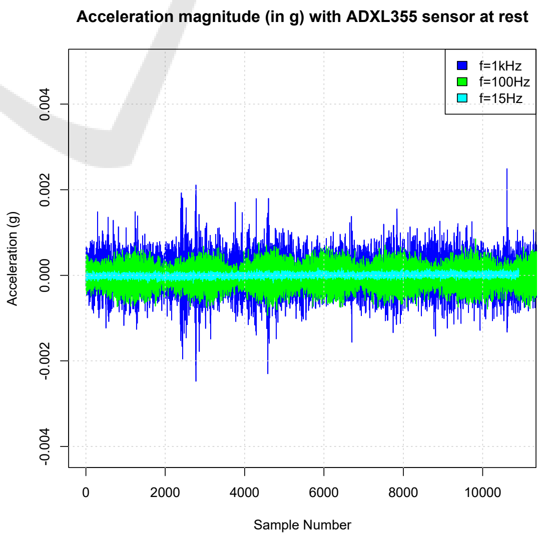

Figure 1: ADXL355 Measured Acceleration Magnitude for different sampling frequencies.

The measured standard deviation for ADXL-355 is presented in Figure 2 and Table 1. Two types are considered for analysis: σ_{min} that represents the "sample window" with lowest sensor noise, and σ_{mean} that provides an indication of the average value of all included σ.

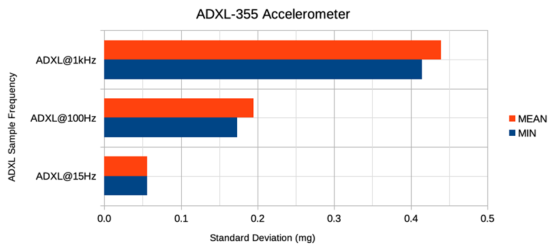

Figure 2: ADXL355 Measured Standard Deviation for different sampling frequencies.

Table 1: ADXL355 Measured Standard Deviation: minimum recorded value and mean value.

ADXL355	σ_{MIN} (mg)	σ_{MEAN} (mg)	Δ (mg)
1000 Hz	0.4143	0.4394	0.0252
100 Hz	0.1734	0.1950	0.0217
15 Hz	0.0555	0.0563	0.0008

As expected, increasing the sample frequency increases sensor noise, resulting in higher dispersion in measurements and thus in a higher standard deviation. The lowest standard deviation value (0.0555mg) was recorded at 15Hz (the lowest sample frequency used) and the highest standard deviation value (0.4143 mg) was recorded at 1KHz). This trend is also present in the difference between σ_{mean} and σ_{min}.

3.1.2 MPU-6050 Measurements

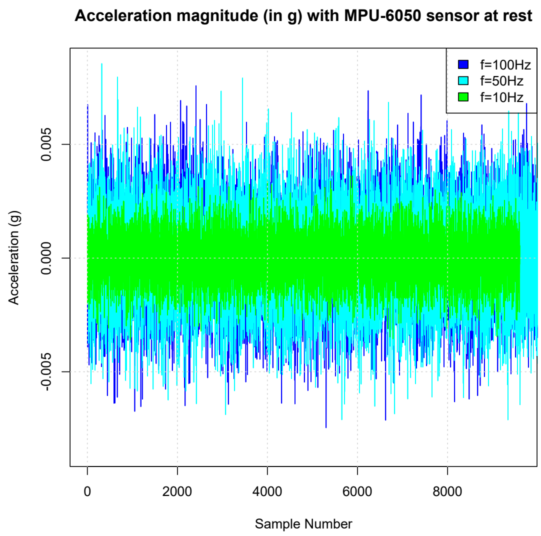

Figure 3: MPU-6050 Measured Acceleration Magnitude for different sampling frequencies

The MPU-6050 is setup to operate in three different sampling frequencies: 5Hz, 10Hz and 100Hz. The measured magnitude acceleration values subtracted by the average (in g) are presented in Figure 3. Once again, the magnitude of the acceleration increases with the sampling frequency.

The measured standard deviation for MPU-6050 is presented in Figure 2 and Table 1. As previously, the analysis considers σ_{min} and σ_{mean}.

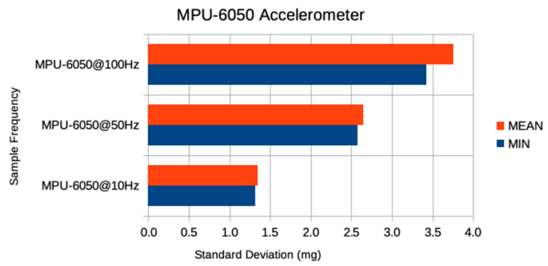

Figure 4: MPU-6050 Measured Standard Deviation for different sampling frequencies

Table 2: MPU-6050 Measured Standard Deviation: minimum recorded value and mean value.

MPU-6050	σ_{MIN} (mg)	σ_{MEAN} (mg)	Δ (mg)
100 Hz	3.4253	3.7606	0.3354
50 Hz	2.5713	2.6515	0.0802
10 Hz	1.3122	1.3472	0.0350

Again, sensor noise increases with the sample frequency: the lowest standard deviation value (1.3122 mg) was recorded at 10Hz (the lowest sample frequency used) and the highest standard deviation value (3.4253 mg) was recorded at 100Hz). This trend is also present in the difference between σ_{mean} and σ_{min}. Moreover, the standard deviation value can also be used to compare sensor noise between different accelerometers: Table 1 and Table shows that, at a sampling frequency of 100Hz, the MPU-6050 standard deviation value is higher (about 20x higher) than ADXL-355, as expected from their respective datasheets.

A comparison between different accelerometers sensor noise is given next.

3.2 Sensor Noise in Smartphones and Dedicated Sensors

In this subchapter, an indication of sensor noise is measured for different accelerometers, including those present in consumer smartphones, operating at the same sampling frequency (100Hz) for purposes of comparing the associated sensor noise. The following devices were analysed:

- A TCL mobile phone
- A Xiaomi mobile phone
- A CAT mobile phone
- Invensense MPU-6050 (used in 3.1.2)
- ST LIS3DHH dedicated accelerometer
- Analog ADXL-355 (used in 3.1.1)

The results are presented next.

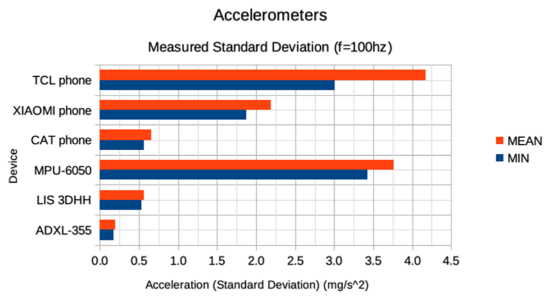

Figure 5: Measured Standard Deviation for several accelerometers operating at a sampling frequency of 100Hz.

Table 3: Measured Standard Deviation for several devices: minimum recorded value and mean value.

Accelerometers	σ_{MIN} (mg)	σ_{MEAN} (mg)
TCL phone	3.0115	4.1707
XIAOMI phone	1.8716	2.1893
CAT phone	0.5595	0.6563
MPU-6050	3.4253	3.7606
LIS 3DHH	0.5270	0.5634
ADXL-355	0.1734	0.1950

The developed method yields an indication of sensor noise, which is sensor specific. As shown in Figure 5 and Table , the dedicated accelerometer ADXL-355 yields the lowest minimum standard deviation (0.1734 mg), followed by the LIS 3DHH (0.5270 mg), the CAT phone (0.5595 mg). The TCL phone and the MPU-6050 yield the highest values, with 3.0115 mg and 3.4253 mg respectively. It is also pertinent to note the disparity between the mean and the minimum value of standard deviation for the TCL phone, indicating that the minimum value for standard deviation alone is not sufficiently robust to assess sensor noise in actual deployments.

3.3 Detectability Threshold Analysis

A potential application of accelerometers consists in measuring ground motion for seismological purposes. In this regard, accelerometers need to have the necessary sensitivity to detect and measure seismic events, which can have different magnitudes. Introduced in Manso et. al (2020), herein it is presented in equation (2) an estimation of the detectability threshold (*DetecT*) of accelerometers, considering their noise level, as measured in 3.1 and 3.2, multiplied by *C*, a constant that is used to increase the assurance that measurements are above noise level:

$$DetecT = \sigma_{accelerometer} \,.\, C \qquad (2)$$

Considering a typical Ground Motion Prediction Equation (GMPE) proposed by Atkinson (2015) and resulting Peak Ground Acceleration (PGA), the accelerometers detectability threshold, depending on the earthquake magnitude and epicentral distance, is presented in Figure 6.

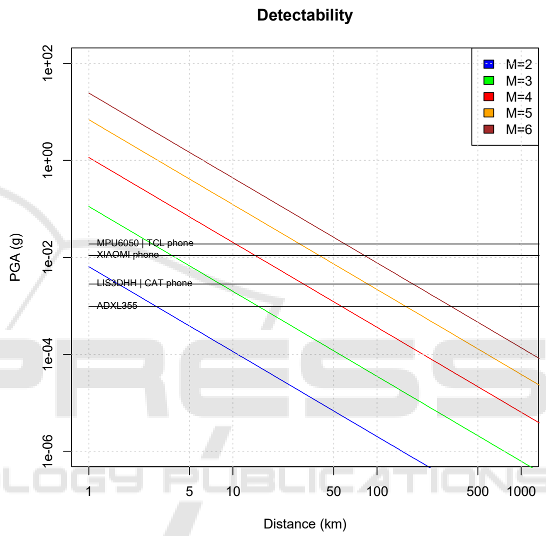

Figure 6: Accelerometers detectability threshold for accelerometers, depending on the earthquake magnitude and epicentral distance.

Using *C*=5 in (2), in a best case scenario, the ADLX-355 is the sensor with the lowest *DetecT*, being capable to detect earthquakes with M=3 and M=5 at a distance larger than 10 km and 100 km respectively. Both the MPU-6050 and TCL phone exhibit similar performance and should be able to detect earthquakes with M=3 and M=5 at a distance of about 2 km and 20 km respectively.

The ADXL-355 accelerometer exhibited the best performance based on the measured sensor noise, thus further analysis is presented. ADXL-355 detectability threshold changes with the chosen sampling frequency, as illustrated in Figure 7. For a M=3 event, the ADXL-355 would be able to detect it at a distance of about 30 Km if operating at a 15Hz frequency, or about 10 Km if operating at a 1000Hz frequency. For a M=5 event, the ADXL-355 at 15Hz would be able to detect it at a distance of about 300

Km. Therefore, applications where the sampling frequency can be lowered will benefit with increased detectability.

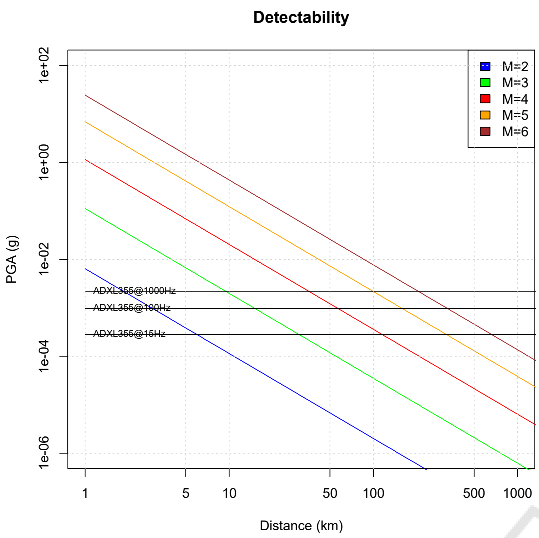

Figure 7: ADXL-355 accelerometer detectability threshold when using different sampling frequencies, depending on the earthquake magnitude and epicentral distance.

Although promising, these findings are preliminary for a more thorough analysis, considering the frequency domain, is required in order to properly assess the sensors detectability threshold.

4 CONCLUSION

Low-cost accelerometers have found numerous real-world applications, including in seismology and risk hazard assessment of buildings and human heritage. Being low-cost, it facilitates their widespread adoption enabling the deployment of high-density networking providing high resolution observation and massive amount of data that may feed intensive processing techniques like big data and artificial intelligence, applying machine learning techniques and pattern matching-based processing that are much more sensitive than the power detectors used in current seismic systems (Addair *et al.*, 2014), making them especially relevant in the presence of noise and weak signals.

This work conducted a preliminary analysis of sensor noise observed in different types of accelerometers, successfully developing a method to measure noise on-site and in-operation. The method produces an indication of sensor noise based on the measured standard deviation. It yields results consistent with sensors specifications (i.e., ADXL-355, LIS 3DHH and MPU-6050) or, when not available, with the observations. Importantly, the method adapts to the sensor's characteristics (e.g., sensor noise), allowing to identify the occurrence of relevant events (i.e., presence of signal), without necessarily knowing *a-priori* the sensor specification (noise is calculated with the sensor in-operation). In addition, this method also adapts to changing circumstances, such as "noise" alterations caused by subtle changes in sensor characteristics (resulting from e.g., small displacements or temperature change). When considering a high-density deployment, logistic and maintenance aspects can represent serious bottlenecks unless the system supports adaptive capabilities, as those here described.

Next steps in this work involve a thorough analysis of the sensor noise characteristics including the frequency domain and against a reference sensor, thus understanding in more depth the applicability of low-cost accelerometers in real-work applications related with seismology, as well as their limitations.

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